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PROTOTYPING DEFENSE SYSTEMS

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Prototyping helps to reduce technical risk in developing weapon systems. While it requires time and money upfront, it allows the government to delay major funding commitments. Thus, prototyping is receiving increased attention now because of lower budgets. Technical risk is a major cause of cost growth and schedule slip, and this paper investigates whether prototyping improves cost and schedule outcomes. The paper develops a framework for examining the level and purpose of prototypes. It examines cost growth and schedule slip for non-prototyped programs and prototypes of various levels and purposes. Results indicate that prototyping helps to make program costs, particularly development costs, more predictable. Prototyped programs take somewhat longer, but the differences may be due to technical complexity. Aircraft and tactical munitions have followed different prototyping strategies, with munitions' strategy being more successful. The analysis provides the basis for prototyping guidelines for use by DoD.

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PREFACE

This document was prepared by the Institute for Defense Analyses (IDA) for the Office of the Under Secretary of Defense (Acquisition), under contract MDA 903 89 C 0003, Task Order T-G7-416, issued 30 June 1987, Amendment 5. The document is in the form of an annotated briefing. The objective of the portion of the study reported on here was to measure the effect of prototyping major weapon systems on cost growth and to develop guidelines for the use of prototyping early in the acquisition process.

The authors would like to thank Mr. John E. Smith, who served as cognizant official for the study. The authors would also like to thank Ms. Donna Pelham, who prepared the manuscript, and Ms. Linda Garlet, who edited the document for publication.

This document was reviewed within the Cost Analysis and Research Division and by Mr. Thomas P. Christie of the Operational Evaluation Division of IDA. One of the authors of this document, D. Calvin Gogerty, is an IDA consultant.

CONTENTS

Prototyping Defense Systems

ISSUES/OBJECTIVES OF OVERALL "EFFECTIVE INITIATIVES" RESEARCH

- **Have defense system program outcomes improved over time?**
  - Present trends of cost and schedule outcomes
- **Have certain acquisition initiatives been effective in improving defense systems program outcomes over the years?**
  - Describe impact of acquisition initiatives on program cost and schedule outcomes
    - MYP
    - Competition
    - Prototyping
    - DTC
    - FPD/TPP
    - Contract incentives
- **What recommendations can be made to improve defense system program outcomes?**
  - Analyze databases and case studies

The prototyping research presented here is part of a larger IDA study, Effective Initiatives in Acquiring Major Systems. The study was concerned with the highly-publicized cost and schedule overruns that have plagued defense programs. Since the 1960s, the Defense Department and defense contractors have pioneered reviews and management initiatives to improve program outcomes. The study undertook a major review of program outcomes in order to determine:

- whether there is a trend toward better outcomes overall.
- whether specific management initiatives have improved outcomes. The study examined multi-year procurement, dual-source competition, prototyping, design-to-cost, fixed-price development, total package procurement, and contract incentives.
- what improvements could be made.

The study found no broad improvements in aggregate outcomes. However, some of the initiatives IDA studied appeared to have potential for improving outcomes [1]. Prototyping was found to be effective, and IDA recommended that guidelines similar to those in use for multi-year procurement be established for prototyping.

SUMMARY OVERVIEW: PROTOTYPING

- **Prototyping lessons learned are positive**
  - obtain better information for EMD decision and technical/schedule/cost risk reduction
  - uncovers surprises
  - but no panacea

- **Quantitative evidence about cost, schedule, quantity benefits of prototyping is positive**
  - development cost more predictable, particularly for challenging programs
  - development quantity growth less
  - production cost growth generally less
  - total development time no different for aircraft, longer for tactical munitions (but probably because of technical challenge)
  - spending in Dem/Val (prototype) phase at lower rate than EMD, thus program cost risk lower

- **Broad guidelines are suggested for prototyping**

The lessons learned from prototyping in the acquisition of major defense systems are overwhelmingly positive. Prototyping helps developers and users to understand the technical risks and uncertainty of the requirements. However, it is not to be suggested that prototyping a system is a panacea and that subsequent development will be trouble-free. Sometimes what is learned from prototyping is what not to do. If you then proceed into engineering and manufacturing development (EMD) with a new and untested approach, you can still run into great difficulty.

The quantitative evidence about the benefits of prototyping is also strongly positive. Prototyping helps to reduce development cost growth, thereby offering improved program control. That effect is particularly pronounced for technically challenging programs. Development quantity growth, the need to build unplanned EMD articles, is significantly less for tactical munitions programs. The benefits of prototyping also carry over into production. Production cost growth is generally less for prototyped systems. These benefits come with some increase in development time. However, this additional time is not necessarily very long (and not statistically significant) for aircraft, and, for the tactical munitions, it may be more related to technical challenge than to prototyping. Prototyping is a leveraged investment. You are buying information relatively cheaply, early in the program, rather than discovering problems in EMD or production, when costs (and rates of expenditure) are higher. Our evidence suggests that prototyped programs do not cost any more than non-prototyped programs.

As a result of our assessment, we suggest broad guidelines (rules of thumb) for prototyping.

WHY CONSIDER PROTOTYPING NOW?

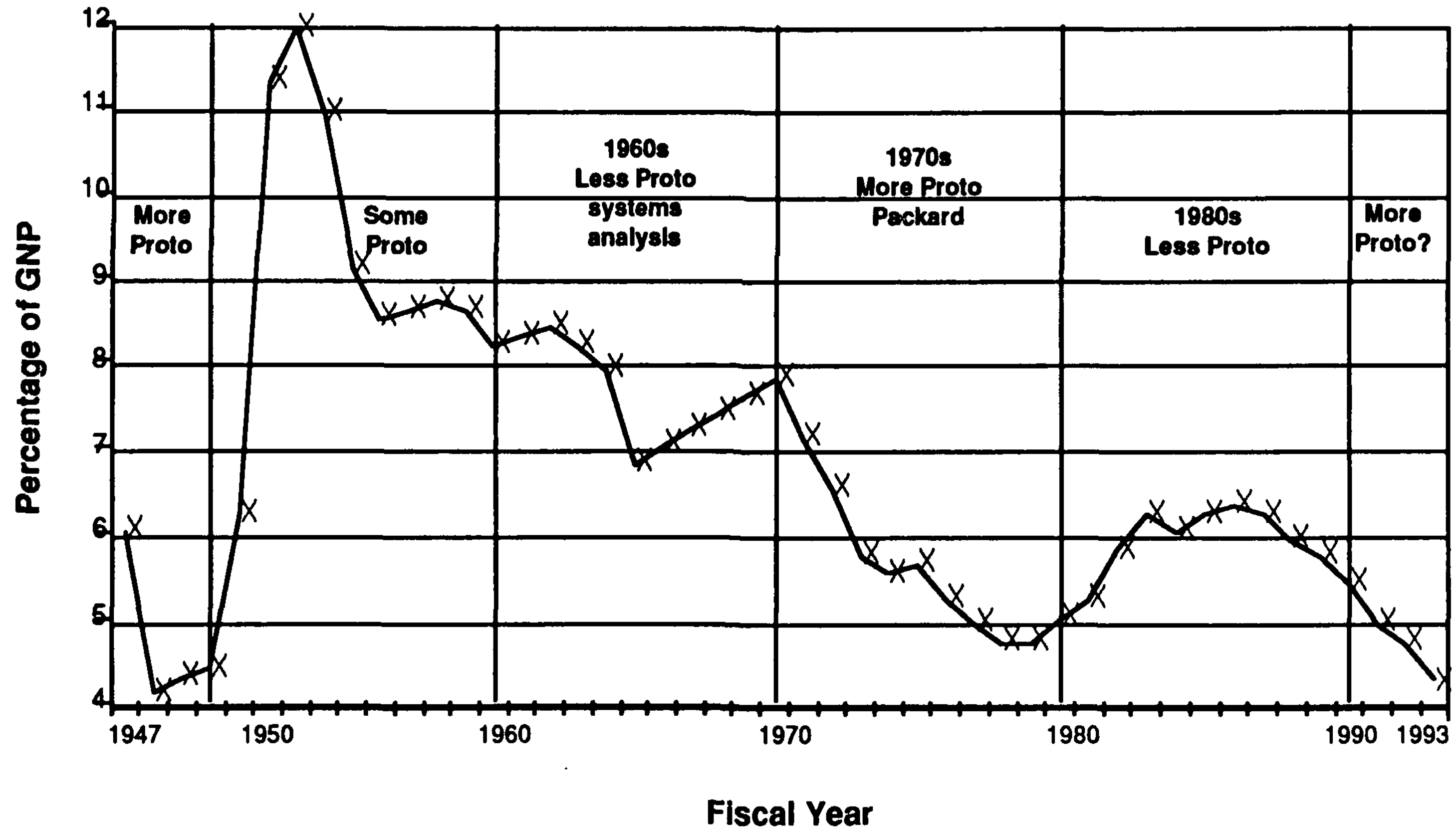
- **Decreasing real defense budget**
- **Reduced funding available for major programs**
- **Fewer new programs–higher risk**
- **Ability of contractors to sustain technology base in question**
- **Threat more unpredictable than ever**
- **Technical sophistication increasing**
  - integration
  - software
  - transition to production

Consideration of prototyping is especially timely now for a number of reasons:

1. A decreasing real defense budget increases pressure on weapon system developers to make their programs more predictable and financially viable.
2. As a consequence of lower overall budgets, reduced funding is available for major acquisition programs.
3. Fewer new starts are anticipated in this lower defense budget climate. Therefore, the programs that are started may tend to be "all eggs in one basket" projects. The few new programs that are funded are likely to carry a great deal of technical risk and to push the state of the art. Since chances to win a bid are becoming increasingly rare, there is a great deal of pressure to underestimate cost and schedule.
4. The ability of the government and contractors to sustain the defense technology base is in question. If not enough work is forthcoming from the DoD, then manufacturers will leave the industry. More importantly, new ideas will not be forthcoming from the technology base, and design teams will wither away. Ben Rich, head of Lockheed's Advanced Development Projects said, "Kelly Johnson [his predecessor] developed 47 different airplanes in his 50 years: In my 40 years, I developed 27 different airplanes: My young engineer today is going to be lucky to see one project—an ATF." [2]
5. Threats to national security are changing as a result of the changes in Eastern Europe, and they are much more difficult to predict.
6. Technical sophistication is increasing. More sophisticated equipment carries even higher technical risk and risks of cost and schedule growth. Integration is becoming more complicated. Software costs are becoming a major part of system costs, and software projects have been difficult in the past. Making the transition from design to production is also a major concern, particularly if early research and development on manufacturing technologies are not addressed by the defense industry.

DoD OUTLAYS AS A PERCENTAGE OF GNP

Prototyping has expanded when DoD Budget has contracted



The chart indicates that when the DoD budget is high, relatively little prototyping is done. There was considerable prototyping in the period of build-down following the Second World War and following the Korean War.

During the early 1960s, there was little prototyping, as the Kennedy administration believed that systems analyses could take the place of prototypes. Less than a third of major systems were prototyped. There was concern about paying for a prototype, finding problems, and then being left with no program or resources to fix the problem.

In the early 1970s, Deputy Secretary of Defense David A. Packard emphasized the importance of prototyping in a fly-before-buy strategy. Around half of major systems were prototyped [1]. During the early 1980s, when the Reagan buildup occurred, once again the defense budget increased relative to GNP, and there was less prototyping. The Packard Commission report in 1986 again called for more prototyping. During the 1990s, as budgets decline, we would expect to see more prototyping.

WHY NOT PROTOTYPE?

"Conventional Wisdom" says:

- Takes too long
- Costs too much
- Slows momentum of program
- Delays large funding commitments
- Evidence of benefits from literature primarily qualitative, technical

Detractors of prototyping suggest several reasons why prototyping should not be undertaken. These include:

1. Takes too long. Decisionmakers may view the prototype phase as added on to the schedule without a prototype, when in fact an advanced development prototype probably saves time in EMD. (Prototyping can save a great deal of EMD time if it solves technical problems early on.) Moreover, even if decisionmakers want to take time savings into account, they may lack tools or models that allow them to do so.
2. Costs too much. Analogously with schedule, detractors regard the up-front cost of prototyping as an obstacle.
3. Slows momentum of the program. By conducting a pre-EMD prototype, program managers and others argue that necessary technical momentum is lost, and getting to initial operational capability (IOC) will take additional time.
4. Delays funding commitment. Along with momentum, major funding commitments tend to be delayed while prototypes are built and tested. In the present acquisition culture, large funding commitments (as in EMD) are viewed as necessary to "lock-in" support. Nevertheless, there is an alternative view that suggests that delaying large funding commitments allows the government to keep its options open.
5. Quantitative benefit not documented. The evidence on prototyping from the literature consists mainly of case studies and qualitative observations.

PROTOTYPING ISSUES

- What is a prototype?
- Why should you prototype?
- What do you learn?
- Are there appropriate guidelines?

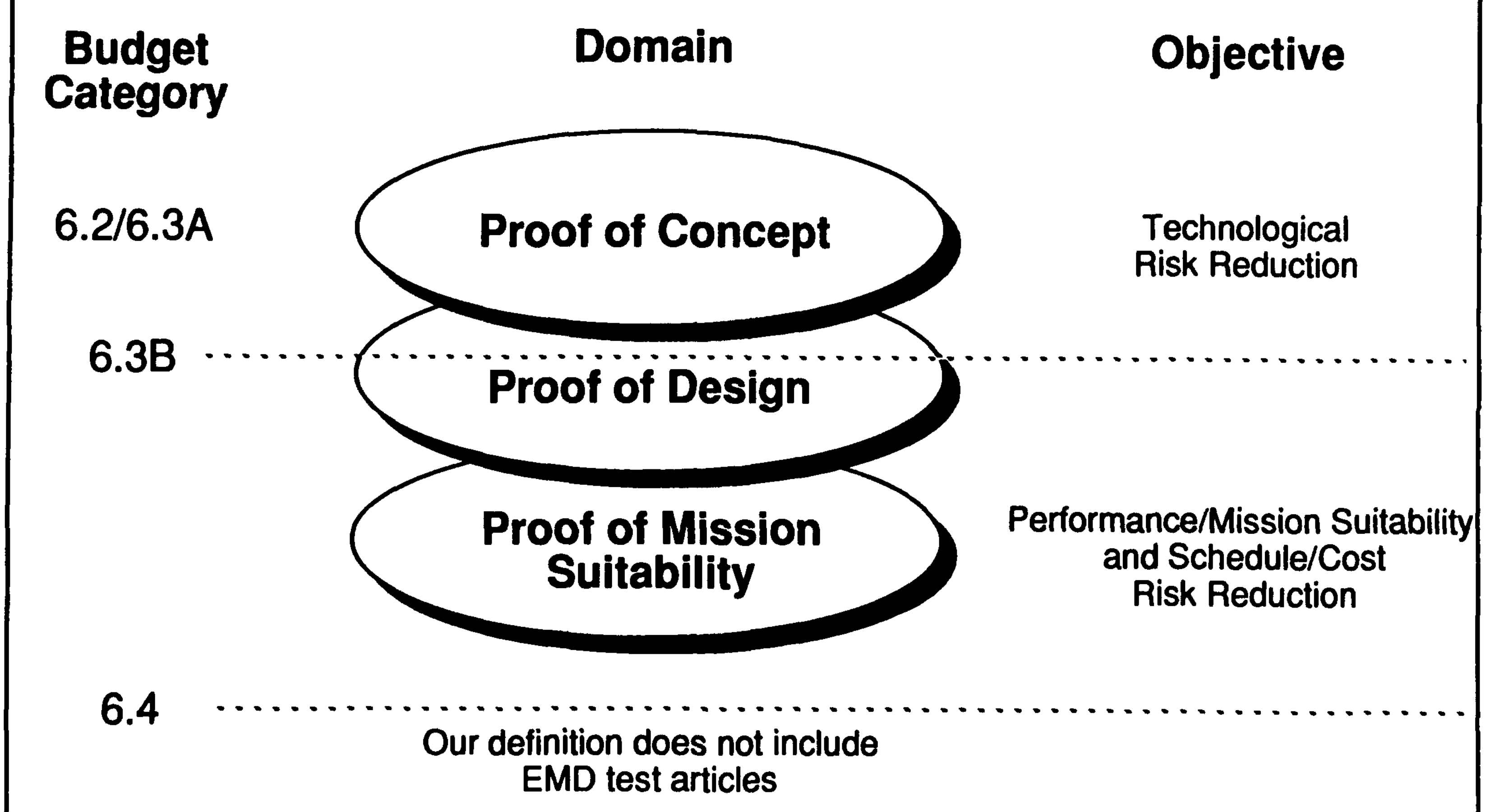
We examined four prototyping issues.

1. What is a prototype? For purposes of this study, a prototype is hardware used for testing, that is built before engineering and manufacturing development (EMD), or full-scale development (FSD) in the case of historical programs. A prototype may have full or partial capabilities and may be full or partial scale. The definition and purposes of prototyping are addressed more fully in the next slide.
2. Why do a prototype? A prototype is used foremost to reduce technical risks, and then to reduce risks with respect to cost, schedule, or operational suitability.
3. What do you learn? You gain information about the feasibility of a concept, the feasibility and cost of a design, and the feasibility, cost, and operational suitability of a particular design.
4. Are there appropriate guidelines? Prototyping, because it involves an up-front investment, may not be appropriate for every equipment type. Therefore, what is needed are guidelines for when prototyping makes sense and for what types of prototypes to undertake.

If the acquisition program is to be successful, potential design problems need to be identified and resolved as early as possible. Such problems can affect the performance and technical characteristics of the weapon, its development schedule, and its development, production, and support costs. A first step is to identify the sensitivity of the weapon's performance and technical characteristics, development schedule, and costs to perturbations in the weapon's design. For those perturbations that result in significant changes in the weapon's performance or technical characteristics, development schedules, or costs, possible risks should be identified and resolved through the construction and testing of prototypes. The earlier that this can be done in the development process, the less will be the subsequent required revisions to the design, manufacturing processes, and already completed parts of the system.

The goal is to identify and resolve design risks as early and as inexpensively in the design process as possible. This suggests that prototypes should be built and tested as inexpensively as possible to demonstrate only what is necessary to resolve the possible risks. This raises questions as to when prototypes should be built and tested in the design process, and the extent to which the prototypes should encompass the entire weapon system.

DEFINING PROTOTYPING



The primary purpose of prototyping is to reduce technical risk. Prototypes can be used to answer three technical questions. The three questions, which are not mutually exclusive, are:

- Is the concept feasible?—Proof of Concept
- Does the design work the way it is supposed to work?—Proof of Design
- Does the system provide a militarily useful capability?—Proof of Mission Suitability

Concept feasibility should be demonstrated before Demonstration/Validation, for both new and modified weapons. The low yield rates attained for many of the electronic subsystem components suggest that manufacturing concepts as well as weapons technology concepts need to be demonstrated.

Whether or not the design works the way it is supposed to work is the focus of most prototyping. For aircraft, this generally includes the airframe, flight controls, and propulsion system but often does not include the full mission electronics. For missiles and electronic systems, this generally includes critical subsystems and may include the complete system. For ships, this generally addresses critical subsystems only, because the cost that would be required to build a complete ship system prototype is prohibitive. For commercial software, alpha and beta test versions serve as prototypes to verify that the software works properly.

Whether or not the system will provide a militarily useful capability depends on the performance and technical characteristics of the weapon in relation to the environment it is to operate in, its development schedule, and the costs to develop, produce, and support it. Evaluation of the military usefulness of the completed design will require a prototype that encompasses most of the weapon's subsystems. There is a spectrum of evaluations, ranging from simple concept demonstrations, to sophisticated testing of complete weapons in realistic environments. For example, a relatively simple test, using a viewing device with a restricted field of view on a maneuvering attack aircraft, could have provided useful information on the target acquisition probabilities for the Improved Infrared (IIR) Maverick very early in the development process.

We examined prototypes for major systems, corresponding to budget categories 6.2, 6.3A, and 6.3B. The analysis focused on 6.3B prototypes. Our definition does not include 6.4 EMD test articles.

EXAMPLE: HARRIER PROGRAM USED ALL THREE TYPES

- **Proof of Concept (Technology Demonstration) –Will it work?**
  - P-1127 (1960)
  - 6.3A low-cost program
- **Proof of Design –Is it practical in operational environment?**
  - XV-6A (1965); led to AV-8A (1971)
  - 6.3B low-cost program
- **Proof of Mission Effectiveness (Mission Demonstration) –Will it work substantially better than what it would replace?**
  - YAV-8B (1976); led to AV-8B (1980)
  - higher cost program

The program that eventually resulted in the AV-8B Harrier aircraft benefited from all three categories of prototyping. The British P-1127 program in 1960 demonstrated the concept and the technology needed and was low-cost.

Proof of design was tested by the XV-6A in 1965, a program that led to the Marine Corps AV-8A in 1971. This was also a relatively low-cost program.

The AV-8A had limited mission capability and an improved version was required by the Marine Corps. In 1976, the YAV-8B prototype underwent mission demonstration testing that demonstrated a doubling of the payload-range capability of the AV-8A. This led to the AV-8B in 1980. The YAV-8B prototype was a high-cost program relative to the earlier prototypes.

WHY AND HOW SHOULD YOU PROTOTYPE?

Prototyping helps primarily to reduce technical risks and uncertainties and thereby reduces schedule and cost risks

- **Austere early research and development**
  - technology demonstration
- **Concurrent developments of critical subsystems**
  - risk reduction (performance/schedule/cost)
- **Early testing**
  - user involvement
  - feedback to designers

Prototyping helps primarily to reduce technical risks. However, such an impact is difficult to measure because the technical characteristics are unique to each equipment type and program. If a program proceeds well from a technical standpoint, then it is much less likely to encounter schedule and cost problems. Cost and schedule problems are measurable. The most successful acquisition programs seem to have in common several elements:

- Austere early research and development (R&D). It is often possible to demonstrate the technology using relatively less resources.
- Concurrent developments of critical subsystems. Examining different versions of a subsystem reduces risk in the overall program.
- Early system performance/operational/mission testing. This increases the probability that the system will work properly and will be used. Ideally, the user is involved at this phase, and results are fed back to designers.

Prototyping fits well with these idealized elements. The building of working hardware very early in the process fits in with austere early R&D. Working models of subsystems are also useful, and early prototyping allows one to test or simulate how well integration is likely to go. Finally, prototyping the hardware early means that there is something to test early on, not just paper designs.

WHAT DO YOU LEARN?

Prototyping information is:

- **Qualitative**
  - design
  - programmatic
- **Quantitative**
  - performance
  - schedule
  - cost

Acquisition managers get two types of information from prototyping—qualitative and quantitative.

The qualitative information can include both design and program information. For example, in the prototype phase for the Lightweight Fighter (later the F-16), the fly-by-wire control and autostabilization system was refined and proven to work [3]. Questions such as: Can a missile achieve lock-on? Can a VTOL aircraft hover in controlled flight? What is the ground effect of vertical engines? Does the guidance system work? can be answered relatively inexpensively. In addition, prototyping yields programmatic information, such as whether contractor teams mesh well and, if there are competing teams, which group has the best design approach.

Quantitative information from prototyping includes performance, schedule, and cost dimensions. Required performance characteristics can be validated through the testing of a prototype, or the requirements can be changed to fit what can reasonably be achieved. Acquisition managers can also learn how long a program will take and how much it is likely to cost.

We cannot evaluate all the benefits of prototyping in a quantitative fashion. The qualitative benefits of prototyping are by definition not quantitatively measurable. In addition, one of the quantitative benefits, performance, is multi-dimensional and has different dimensions across equipment types. However, schedule and cost are measurable, and by measuring planned vs. actual schedules and costs, we can compare program outcomes across equipment types.

RECENT EXPERIENCE: LOCKHEED YF-22

"If we had gone, as was the original plan, directly into a full-scale development program from a paper demonstration/validation program, we probably would have a pretty big schedule and cost problem on our hands."

—Sherman H. Mullin, Lockheed YF-22 General Manager

- Materials—actual use of composite thermoplastic/thermoset materials different from expectations in early design
- Aerodynamics/configuration blending for low observables (LO)—simulations weren't enough—one year extra to freeze design
- Software—working large packages—reducing size took "couple of years"
- Joint venture—teaming arrangements took time to achieve workable system
- Engineering changes (CAD/CAM)—fewer changes once process was set up

Here is one recent example of the benefits of prototyping in an actual program: the winning model for the Advanced Tactical Fighter, the Lockheed YF-22. The general manager for the program said that the prototype phase yielded information that probably prevented considerable cost and schedule growth.

The ATF is taking major technical leaps in multiple areas. The competitive prototype phase allowed exploration and resolution of many technical issues while spending was relatively low.

PROTOTYPING DATABASE

- **52 Programs (17 Prototypes)**
  - 18 Aircraft (8 Prototypes)
  - 21 Tactical Munitions (9 Prototypes)

- **7 Tactical Aircraft Schedule (3 Prototypes)**

No outcome measures for ship or ground vehicle programs

No non-major programs

Incomplete data set on subsystem prototypes

We were fortunate to have a large sample of major acquisition programs—those meeting the dollar threshold for filing Selected Acquisition Reports (SARs)—from a number of past IDA studies. Because of the modest level of effort, we did not collect original data for the study. The data we had were particularly appropriate for a study of prototyping, since they have uniform outcome measures for a wide variety of programs. Most of the data were from the Effective Initiatives study [1]. The tactical munitions data is from an IDA study of acquisition experience for that type of equipment [4] and from an IDA study of tactical missile schedules [5]. The tactical fighter data is from Effective Initiatives [1] and a study on tactical aircraft schedules [6].

The tactical aircraft cost-estimating relationships (CERs) are from the IDA tactical aircraft development cost study [7], and the munitions CER is from Yates, Waller, and Vaughn [8].

For evaluation of cost and schedule growth outcomes, we employed the 52 programs in the Effective Initiatives study that had at least three years of data and that were not canceled, e.g., programs that bought or will buy at least three-quarters of the number of items planned. The appendix to this document contains a list of the programs and the data.

There are some limitations in the data. We could not fully identify subsystem prototypes. Because we did not have cost growth measures for them, we omitted ship and vehicle programs.

PROGRAM OUTCOME MEASURES (ACTUAL/PLANNED RATIOS)

- **Development**
  - cost and cost growth
  - schedule and schedule growth
  - quantity and quantity growth
- **Production**
  - cost and cost growth
  - schedule and schedule growth
  - quantity and quantity growth
- **Total Program**
  - cost and cost growth

Cost Growth was adjusted for quantity (Development Estimate) and inflation

Because weapon systems are very dissimilar, analysts search for a common yardstick to measure program success. Over the last forty years, much has changed in the weapon acquisition process. However, there are some common threads.

Since the late 1960s, current estimates of program cost and schedule for major programs have been reported in Selected Acquisition Reports. These current estimates are compared with original estimates at Milestone II to get some sense of how much cost and schedule growth the program has experienced. Programs that experienced a high level of cost growth are judged to be less successful than programs that had less cost growth. Analogously, programs that took much more time than planned from Milestone II full-scale development (FSD) (now EMD) to initial operational capability (IOC), are judged to be less successful, while those that met their schedule targets are thought of as being more successful. Such measures have the virtue of being index numbers that can be used to compare diverse systems using a similar benchmark.

As in the earlier study on Effective Initiatives, cost growth was adjusted for changes in production quantity and inflation.

SUMMARY OF QUANTITATIVE FINDINGS

Cost

- **Total development cost growth significantly less for prototypes**
  - 17% vs. 62% overall
  - 21% vs. 106% for munitions
- **Fewer unplanned EMD articles**
- **Production cost growth less**
  - 29% vs. 55% overall

Schedule

- **Prototyped programs take about 2 years longer from MS 1 to IOC overall**
- **No statistically significant difference for aircraft from MS 1 to IOC**
- **Increased time from MS 1 to IOC for prototyped munitions (compounded by complexity), EMD length no different**

1. Cost and Cost Growth

   a. Development Cost Growth Lower. Development cost growth was significantly less for prototyped programs than for non-prototyped programs. Thus, DEM/VAL prototyping allows program managers to make a more educated cost estimate at the time of Milestone II. Average cost growth was 62 percent for non-prototyped systems, and only 17 percent for prototyped systems. The effect was smaller, 29 percent vs. 17 percent (and not statistically significant), for all aircraft programs. (Among the tactical aircraft programs, non-prototyped programs grew by 18 percent and prototyped programs by 12 percent.) The tactical munitions showed the greatest payoff to prototyping. For non-prototyped programs, development cost more than *doubled* from its plan at EMD. Prototyped munitions had only 21 percent development cost growth. The data on cost growth are arrayed in the appendix to this document.

      We also tested whether program size had a confounding effect on development cost growth, independent of prototyping. Larger programs tend to have lower cost growth generally, perhaps because of increased management attention. In the aggregate and in tactical munitions, program size did have a significant negative effect on development cost growth. Nevertheless, prototyping remained as a significant factor in reducing development cost growth, independent of program size.

   b. Fewer Unplanned EMD Articles. Prototyped programs have significantly fewer unplanned EMD articles. On the basis of prototype testing, program managers are able to make a better estimate of how many EMD articles they will need.

   c. Production Cost Growth Lower. While the difference was not statistically significant, production cost growth was less for the prototyped systems than for the non-prototyped. Average cost growth was 55 percent for non-prototyped systems, and only 29 percent for prototyped systems.

   d. Levels of Development and Production Cost. To examine the effect of prototyping on the levels of development and production costs, we turned to a standard tool of cost analysis, cost-estimating relationships (CERs). CERs relate technical characteristics of a weapon system to its development or production cost. We examined the residuals of the CERs to determine whether there was any significant difference between prototyped and non-prototyped systems. If we found that prototyped systems had significantly higher residuals, this would indicate that a system with given technical characteristics would cost more if it were prototyped. Conversely, if we found that prototyped systems had significantly lower residuals, it would indicate that prototyped systems generally cost less than non-prototyped systems.

We were able to perform the tests for three equations: a tactical aircraft airframe full-scale development CER, a tactical aircraft production CER, and a tactical munition full-scale development CER. For tactical aircraft airframes, there is no significant difference in either development or production costs that could be explained by prototyping. In the case of tactical munitions, there is no significant difference in development costs between prototyped and non-prototyped systems. (We were unable to locate a sufficiently aggregated CER to test munitions production costs). Thus, the available evidence on total costs suggests that prototyped systems of equivalent technical capability do not cost significantly more or less than non-prototyped systems.

2. Schedule

Overall, prototyped programs took 2 years longer than non-prototyped programs from Milestone I to IOC (significance level=.06), but prototyping made no difference in the time from Milestone II to IOC. For the aircraft, there was no statistically significant difference in either interval. Prototyped aircraft took slightly less than 9 months longer from Milestone I to IOC (117 vs. 108 months), but Milestone II to IOC times were virtually identical (69.6 vs. 70.4 months). The prototyped munitions took over 2 years longer than non-prototyped munitions (135 vs. 104 months), but the difference was not statistically significant. (Moreover, the more complicated munitions were prototyped. When we control for this relationship, the time difference decreases to 1 year.) The length from Milestone II to IOC was actually 5 months shorter for the prototyped munitions, but again not statistically significant.

Thus, prototyping may take some additional time. This time, however, must be weighed against the gains in cost and technical predictability. In addition, the extra time occurs at a time in the program when spending rates are low.

3. Competitive Prototypes

The following systems were identified as having competitive prototypes: F-16, A-10, UH-60A, AH-64A, AMRAAM, MLRS, and Sparrow AIM-7M. The competitive programs were more extensive than the other prototypes. All except the AIM-7M were full or partial operational suitability prototypes.

The competitive prototypes for munitions were more successful than those for aircraft. The munitions prototypes were particularly successful in terms of fewer unplanned FSD articles.

One can see the benefits of competitive prototyping more clearly by looking at individual cases. In the case of the AH-64, for example, prototyping aided in source selection and allowed many changes in design early in the process [3]. Time and again, program management staffs have commented that contractors are much more responsive to requirements in the competitive phase of a program [1].

Competition may be more valuable in a situation where there is a great deal of technical risk, because it allows contractors to try different sets of solutions to a problem. Competitive prototyping also enhances competition in the defense industry. The requirement that contractors produce an actual model for a fly-off competition helps to keep contractors on their toes. It also makes it more difficult for the type of bid revision that caused trouble in the "Ill Wind" incident to occur, because the prototype is part of the bid [9].

4. Level and Purpose of Prototype

We performed tests to see whether a particular level (full system vs. partial vs. subsystem) or a particular purpose (concept vs. design vs. operational suitability) of prototyping was more effective in preventing development cost growth. We found significant results in only two areas, and both of these have caveats attached. First, for the tactical aircraft, there was only a single full-system prototype, the F-5E. It had significantly lower development cost growth than the partial-system prototypes among the tactical aircraft. (Recall that we did not have good data on aircraft subsystem prototypes.) Second, among the munitions, subsystem prototypes had significantly lower development cost growth than full-system prototypes.

EXPERIENCES THAT SHOULD INFLUENCE THINKING ABOUT PROTOTYPING

- **Early realism regarding achievable requirements is a major benefit of prototyping: knowing what you can buy**
  - ATF: Over 20 changes in major requirements before prototype flew
  - F-111 non-prototype: Held to requirement at great cost

- **Cross-program benefits from competitive prototyping: Lightweight Fighter competition**
  - Winning prototype YF-16 became F-16
  - Losing prototype YF-17 led to F/A-18

- **Despite prototyping or prior experience, mandated IOC can lead to serious problems**
  - AMRAAM
  - B-1B

In addition to the quantitative analysis of historical programs, we examined other recent experiences that we believe should influence thinking about prototyping.

A major benefit of prototyping is early realism. In an atmosphere of reduced funding and congressional skepticism of any new weapon programs, prototyping lets you know early on how much capability you can afford to buy. This is particularly important for programs with revolutionary technologies.

The ATF program is a prime example. All three major components of the aircraft include new technologies—the airframe has composite thermoplastic/thermoset materials; the engine is completely new; and the avionic suite has increased capabilities and new software packages. A prototype competition kept both contractor teams working to develop realistic designs early. As a result of the prototype effort, 20 changes were made in major requirements before the prototype flew. Approximately one-tenth of the projected total cost of EMD was spent on the prototypes, and for that investment the government received flying aircraft that provided the basis for a source selection.

Contrast that experience with the Navy's A-12 stealth fighter program. The major challenge of that program was the coordination of stealth technology with carrier landing requirements. However, the government pursued an acquisition strategy that was very different from that of the ATF. The A-12 program went directly into FSD on the basis of a paper design competition. A single source was awarded a fixed-price development contract. When the technical challenges proved more difficult than expected, the program faced major cost and schedule problems at a time when the spending rate was very high. While the fixed-price development contract put the contractor rather than the government at risk, the government was concerned that it would have to bail out the contractor eventually. The requirements were scaled back, but by that time, the problems in the program had surfaced, and the DoD canceled it. People who make funding decisions appear willing to tolerate fits and starts when spending levels are relatively low, but they are less willing to accept surprises when they are making large commitments.

The F-111 was built during the 1960s without a prototype. Again, the requirements were very challenging for the time—great speed at low altitude for a relatively heavy aircraft. The requirement was held to and eventually met, but at a 75 percent higher cost than was originally planned.

Some benefits of prototyping spill over into other programs, and we could not measure these in the quantitative analysis. They are nonetheless important. For example, the prototype competition in the F-16 program actually yielded two aircraft. The winning YF-16 prototype built by General Dynamics became the F-16, and the losing YF-17 prototype built by Northrop eventually became the F/A-18. Both aircraft first flew in the late 1970s and are still in use today. In addition, as discussed earlier, a pattern of prototyping, particularly competitive prototyping, over the years helps promote competition among contractors.

The final experience we want to highlight is that prototyping is no cure-all for acquisition problems. Even with prototyping, some programs are faced with trying to do too much too fast. Mandated IOC dates can lead to serious problems, particularly when requirements are relatively inflexible.

In the AMRAAM (AIM-120) program, the objective was to package a shorter-range version of a fire-and-forget capability into a much smaller package than the AIM-54C Phoenix. The prototypes used solid-state electronics to do this, and they were not successful. The prototype phase told designers one thing that would not work. Nevertheless, program officials, rather than exploring other options as prototypes, were allowed to proceed into full-scale development under pressure of a mandated IOC. The FSD version reverted to the traveling-wave-tube technology, but the program has experienced considerable cost and schedule growth.

The B-1B program did not have a formal prototype phase, but it was a successor to the B-1A and so benefited from prior experience. The one thing that the B-1A did not have was defensive avionics. Believing the B-1B to be a relatively simple extension of the B-1A, Congress required an IOC of September 1986. The development team could not take the time to figure out how to make the defensive avionics work properly before IOC and spent considerable resources fixing problems afterwards.

Prototyping enhances the credibility of major programs, particularly given the tendency to underestimate technical risk.

GUIDELINES: WHEN AND HOW TO PROTOTYPE

What Kinds of Systems

- New performance technology for the contractor(s)
- New manufacturing technology for the contractor(s)
- High cost per unit and large quantity
- Long lead time and/or high cost to correct potential unforeseen problems

How to Prototype

- Generally the earlier the better
- Concept demonstration particularly important for all-new systems
- Operational suitability particularly important in tight funding environments
- Depends on type of risk
  - Technical risk: concept and design
  - Requirements uncertainty: operational suitability
  - Development cost and schedule uncertainty: concept and design
  - Production cost, producibility: add mission demonstration

Based on our qualitative and quantitative analyses, we present here recommendations for the types of systems to be prototyped, and how to prototype.

What Kinds of Systems:

1. When the program involves a new performance technology for the contractor (even if the technology has been demonstrated by another contractor), the technology should be prototyped. New or significantly improved guidance and control systems for missiles should always be prototyped. New or significantly improved engines should always be prototyped.
2. When the program involves a new manufacturing technology for the contractor (even if the technology has been demonstrated by another contractor), the technology should be prototyped.
3. Systems with a high cost per unit that are to be produced in large quantities should be prototyped.
4. When solutions to potential problems would require large amounts of time and money, the system should be prototyped.

How to Prototype:

In general, the earlier the prototyping strategy is undertaken, the better. For all-new systems, the concept demonstration phase is particularly important. Operational suitability prototyping is particularly important in times of budget crunch, since we are particularly eager to know whether a system will work significantly better than what we already have.

The type and extent of prototyping to be done also depends on the nature and extent of risk in the program. If the risk is largely technical, then concept and design prototyping are the most important. If the risk is that requirements are uncertain, then proving the technology is operationally suitable is most important. If there are concerns about production costs and producibility, it may be necessary to add a test of operational suitability with production article(s).

Competition is particularly important when there is technical risk. In such a case, it is worthwhile to carry competition up to EMD. Competitive prototypes have been found to enhance competition both within a competitive program and across programs. However, the payoffs to competition after EMD are uncertain, and depend on many factors.

GUIDELINES: HOW MUCH IS IT WORTH INVESTING?

- **Need more analysis to refine guidelines on cost**
- **Prototyping is a leveraged investment—spend small dollars to avoid large surprise**
- **Prototype cost should probably be less than the highest estimate of:**
  - 25% of EMD cost estimate
  - 10% of acquisition cost estimate (EMD and Procurement)
  - 5% of life-cycle cost estimate
- **Prototype costs can be captured and used to refine EMD and procurement cost estimates**

Our quantitative analysis was not extensive enough to support development of a cost/benefit model for prototyping. Nevertheless, we believe that we have taken some important first steps toward such a model.

Prototyping is a leveraged investment. Spend small amounts of money now to avoid large surprises later. As rules of thumb for when prototyping makes sense relative to its likely payoff, we suggest that the prototype cost should be less than 25 percent of the EMD cost estimate, 10 percent of the acquisition cost estimate (EMD and Procurement), or 5 percent of the life cycle cost estimate, whichever is highest.

These rules of thumb can be adapted for technical risk and schedule criticality. If technical risk is high, then the cost estimates upon which these rules of thumb are based have considerable risk attached to them. For example, if technical risk is low, schedule is critical, and a prototype would cost 20 percent of EMD cost, then it would not make sense to undertake one. On the other hand, if technical risk is known to be very high, schedule is not critical, and a prototype would cost 30 percent of the EMD cost estimate, then prototyping makes sense.

The costs of prototypes can be captured and used to refine EMD and procurement cost estimates. The literature on this subject is surprisingly sparse.

CONCLUSIONS

- **Prototyping experience is positive**
  - Development costs more predictable
  - Production cost growth lower

- **Strategy of prototyping challenging programs (e.g., munitions) has had biggest payoff**

- **Prototype important and challenging programs**

Prototyping helps to uncover problems at a time when fixing them is relatively cheap. In 1972, David Packard said: "A few months ago at a meeting of military project managers, someone objected to extensive testing because it would delay the program. He complained that testing showed up things that needed to be fixed and it took time to fix them, and this would delay the initial operating capability. Unless we get rid of that kind of thinking there will be no hopes."

The two equipment groups in our study that had the most prototyping were aircraft and tactical munitions. We observed very different strategies regarding the prototyping of these two groups. Among the aircraft, the systems pushing the state of the art the least (such as the F-5E and the F-16) were prototyped, while others that were more technically difficult (like the F-14) were not. In the munitions, the opposite occurred. Systems with a high level of technical "reach" like Hellfire, HARM, and Harpoon were prototyped.

The strategy used for munitions was the more successful of the two. Munitions are often high-risk programs in general. They are less glamorous than aircraft and therefore seem to get less management attention. Perhaps the building and testing of a prototype serves to focus attention on the program. In any event, the munitions strategy was strongly successful. We would expect the munitions with high technical reach to have higher cost growth than those with low reach. In fact, those complicated munitions that were prototyped did *better* than the simple ones that were not prototyped.

In the aircraft, by contrast, the prototyping strategy did not seem to be as successful. However, when we remove the helicopters, which had generally higher cost growth regardless of prototyping strategy, the remaining prototyped aircraft have significantly lower development cost growth than the non-prototyped aircraft.

Prior studies of prototyping have been qualitative and have emphasized the uniqueness of each acquisition. Despite this uniqueness, policymakers should use consistent, clear lessons from past programs to set strategy for new programs. The quantitative and qualitative evidence we examined is clear. The payoff to prototyping challenging systems is large.

POSSIBLE EXTENSIONS

- **Prototype decisionmaking**
  - program cost/benefit assessment tool
  - methods for improving technical risk estimates

- **Other effects/forms of prototyping**
  - prototyping in combination with other initiatives
  - macro impact of prototyping and implementation strategy

This analysis could usefully be extended in two major directions:

1. Prototype decisionmaking
   - Measure the magnitudes of the costs and benefits of prototyping. Examine schedule differences for prototyped and non-prototyped programs.
   - Develop better measures of technical risk early in the acquisition process.
2. Other effects/forms of prototyping
   - Prototyping in combination with other initiatives such as design-to-cost and contract incentives.
   - Impact of prototyping across programs, including its effect on competition and the ability of industry to develop and produce new, technologically sophisticated weapon systems.

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APPENDIX

DATA

PROGRAMS IN PROTOTYPING DATABASES

	AIRCRAFT				TACTICAL MUNITIONS			STRATEGIC
	TACTICAL	ELECTRONIC	OTHER	HELICOPTERS	AIR-LAUNCHED	SURFACE-LAUNCHED	SATELLITES	MISSILES
NON-PROTOTYPED	F-14D F-15 F-14A F/A-18	E-6A EF-111A E-2C EA-6B S-3A	T45TS B-1B	CH-47D	SPARROW F SIDEWINDER L TOW 2 SIDEWINDER M PHOENIX C MAVERICK A	MK48 AD STD MSL 2 IMPHAWK SHILLELAGH STINGER LANCE	DMSP NAVSTAR-GPS DSP DSCS3	TRIDENT 2 PEACEKEEPER GLCM TOMAHAWK MINUTEMAN 2 SRAM MINUTEMAN 3
PROTOTYPED	AV-8A F-5E F-16 AV-8B A-10	LAMPS MK 3		UH-60A AH-64A	AMRAAM PHOENIX A HELLFIRE HARM HARPOON MAVERICK SPARROW M	MLRS MK50		

PROTOTYPING DATABASE

PROGRAM	PROTO	SYSTEM	PARTIAL	SUBSYST	CONCEPT	DESIGN	OPSUIT	COMPETE	DCG	DSG	DQG	PCG	TPCG	M1IOC	M2IOC
A-10	1	0	1	0	0	1	1	1	1.27	1.08	0.71	1.34	1.33	94	57
AH-64A	1	0	1	0	1	1	1	1	1.26	1.49	1.00	1.74	1.59	165	115
AMRAAM	1	1	0	0	0	1	1	1	1.40	1.73	0.66	.	.	138	92
AV-8A	1	0	1	0	1	1	0	0	.	.	.	0.99	0.99	.	.
AV-8B	1	0	1	0	0	1	0	0	1.11	0.83	1.00	0.77	0.82	112	73
F-16	1	0	1	0	0	1	1	1	1.05	0.98	1.00	1.21	1.19	83	40
F-5E	1	1	0	0	0	1	1	0	1.05	1.06	1.00	0.79	0.88	.	19
HARM	1	1	0	0	0	1	1	0	1.42	1.21	1.00	1.39	1.47	132	69
HARPOON	1	1	0	0	0	1	1	0	1.06	1.08	1.00	1.93	1.53	88	49
HELLFIRE	1	1	0	0	0	1	0	0	1.09	1.44	0.95	1.61	1.39	145	125
LAMPSMK3	1	1	0	0	0	1	1	0	1.04	1.00	1.00	1.17	1.13	144	82
MAVERICK_IIR	1	0	0	1	1	1	0	0	1.07	1.98	0.94	1.58	1.53	211	113
MK-50	1	1	0	0	0	1	0	1	1.27	1.29	1.00	.	.	141	87
MLRS	1	1	0	0	0	1	1	1	1.03	1.05	0.72	0.94	0.95	.	74
PHOENIX_A	1	1	0	0	0	1	0	0	1.54	1.19	0.82	1.35	1.39	132	56
SPARROW_M	1	0	0	1	1	1	0	1	0.98	1.46	1.00	1.31	1.29	96	57
UH-60A	1	1	0	0	0	1	1	1	1.08	1.07	0.63	1.25	1.22	101	101

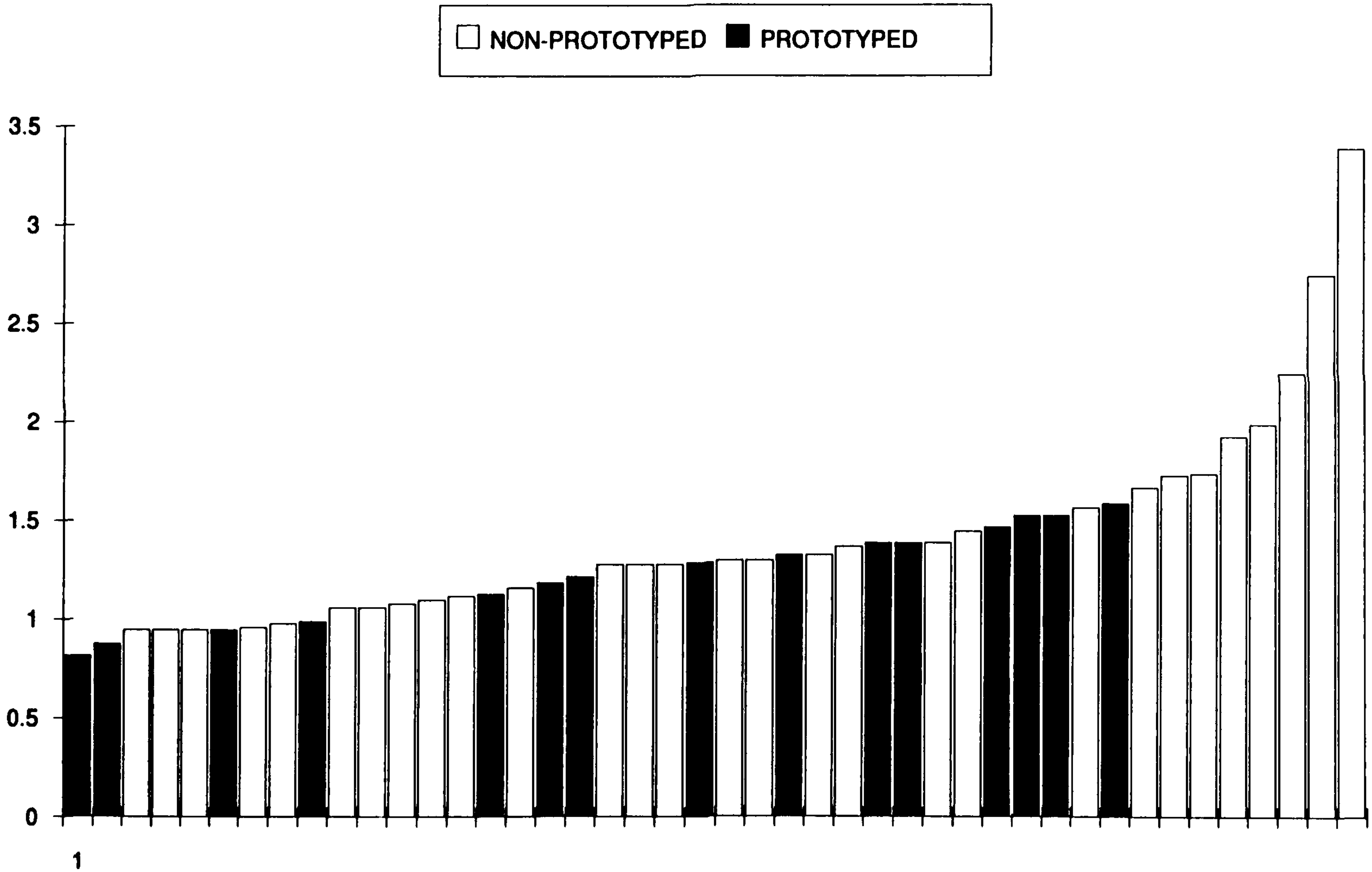
Definitions:

COMPETE	1=competitive prototype (two or more sources), 0=not competitive prototype
CONCEPT	1=concept prototype, 0=not concept prototype
DCG	Development cost growth index (planned/actual ratio)
DESIGN	1=design prototype, 0=not design prototype
DSG	Development schedule growth index (planned/actual ratio)
M1IOC	Months from Milestone I to IOC (preliminary data)
M2IOC	Months from Milestone II to IOC (preliminary data)
OPSUIT	1=operational suitability prototype, 0=not operational suitability prototype
PARTIAL	1=partial system prototype (for aircraft, generally omits avionics), 0=not partial system prototype
PCG	Production cost growth index, adjusted for quantity (planned/actual ratio)
PROTO	1=prototyped, 0=not prototyped
SUBSYST	1=subsystem prototype, 0=not subsystem prototype
SYSTEM	1=full system prototype, 0=not full system prototype
TPCG	Total program cost growth index (planned/actual ratio)

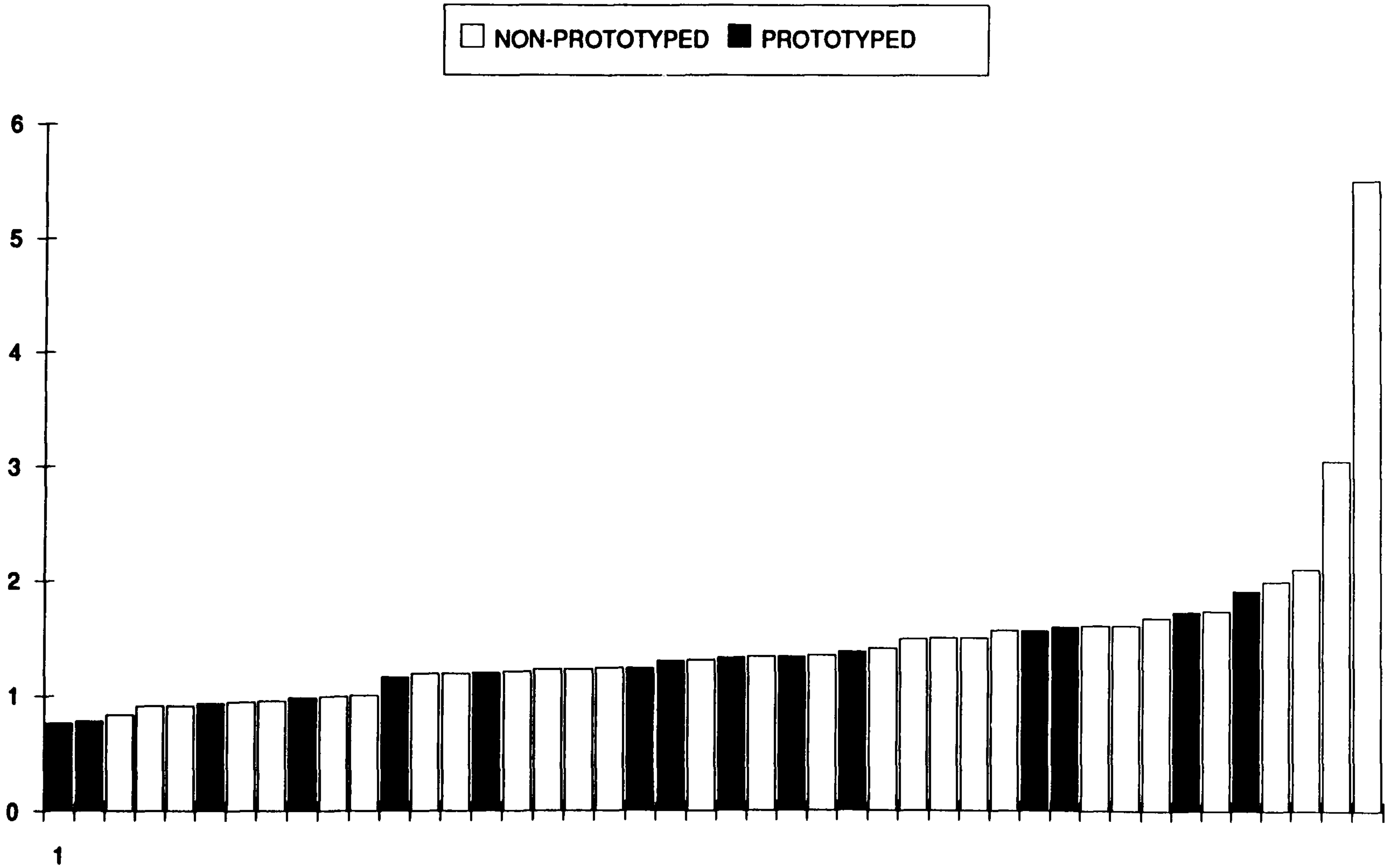
PROTOTYPING DATABASE

PROGRAM	PROTO	SYSTEM	PARTIAL	SUBSYST	CONCEPT	DESIGN	OPSUIT	COMPETE	DCG	DSG	DQG	PCG	TPCG	M1IOC	M2IOC
B-1B	0	0	0	0	0	0	0	0	0.96	1.00	.	0.95	0.95	.	56
CH-47D	0	0	0	0	0	0	0	0	1.13	1.06	1.00	1.35	1.33	.	100
DMSP	0	0	0	0	0	0	0	0	1.00	1.00	1.00	0.92	0.95	.	.
DSCS3	0	0	0	0	0	0	0	0	2.54	1.59	1.00	1.75	1.99	.	102
DSP	0	0	0	0	0	0	0	0	1.35	1.00	1.00	1.00	1.06	.	.
E-2C	0	0	0	0	0	0	0	0	1.50	0.76	1.00	1.22	1.28	68	41
E-6A	0	0	0	0	0	0	0	0	1.12	1.27	1.00	0.92	0.96	99	84
EA-6B	0	0	0	0	0	0	0	0	1.26	1.00	1.00	1.32	1.30	.	41
EF-111A	0	0	0	0	0	0	0	0	2.10	1.70	1.00	1.62	1.73	.	107
F-14A	0	0	0	0	0	0	0	0	1.44	1.16	2.00	1.25	1.28	73	58
F-14D	0	0	0	0	0	0	0	0	1.07	1.00	.	.	.	.	.
F-15	0	0	0	0	0	0	0	0	1.07	1.03	1.00	1.20	1.16	125	68
F/A-18	0	0	0	0	0	0	0	0	1.15	1.08	1.00	1.42	1.37	138	86
GLCM	0	0	0	0	0	0	0	0	3.48	1.30	0.83	1.62	1.67	.	83
IMPROVED HAWK	0	0	0	0	0	0	0	0	1.87	1.25	1.00	3.07	2.75	.	96
LANCE	0	0	0	0	0	0	0	0	1.08	1.46	1.09	1.20	1.12	.	54
MAVERICK_A	0	0	0	0	0	0	0	0	1.15	1.46	0.91	0.84	0.95	74	55
MINUTEMAN2	0	0	0	0	0	0	0	0	1.00	1.71	1.00	1.24	1.06	67	24
MINUTEMAN3	0	0	0	0	0	0	0	0	0.98	0.87	0.73	1.69	1.39	72	27
MK-48_ADCAP	0	0	0	0	0	0	0	0	1.01	1.35	1.00	.	.	107	71
NAVSTAR_GPS	0	0	0	0	0	0	0	0	0.99	1.44	1.00	1.24	1.08	.	
PEACEKEEPER	0	0	0	0	0	0	0	0	0.96	1.00	1.00	1.51	1.28	129	96
PHOENIX_C	0	0	0	0	0	0	0	0	1.67	1.45	1.50	2.01	1.93	122	122
S-3A	0	0	0	0	0	0	0	0	1.09	1.00	0.67	1.36	1.30	65	54
SHILLELAGH	0	0	0	0	0	0	0	0	1.31	1.05	1.38	1.51	1.45	.	96
SIDEWINDER_L	0	0	0	0	0	0	0	0	4.89	2.45	4.10	2.12	2.25	81	81
SIDEWINDER_M	0	0	0	0	0	0	0	0	2.04	1.01	1.94	1.01	1.10	.	79
SPARROW_F	0	0	0	0	0	0	0	0	4.27	2.82	3.94	1.58	1.74	124	124
SRAM	0	0	0	0	0	0	0	0	2.80	2.03	.	5.53	3.39	83	65
STD_MSL2	0	0	0	0	0	0	0	0	1.44	1.00	1.00	.	.	.	.
STINGER	0	0	0	0	0	0	0	0	2.34	1.06	1.00	.	.	160	105
T45TS	0	0	0	0	0	0	0	0	0.44	1.04	0.50	.	.	190	80
TOMAHAWK	0	0	0	0	0	0	0	0	1.66	1.48	0.91	1.50	1.57	124	89
TOW2	0	0	0	0	0	0	0	0	1.70	1.02	1.00	0.96	0.98	60	60
TRIDENT2	0	0	0	0	0	0	0	0	0.93	1.00	0.93	.	.	113	77

TOTAL PROGRAM COST GROWTH RATIO



PRODUCTION COST GROWTH RATIO



DEVELOPMENT COST GROWTH RATIO